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The jet/interstellar medium interaction and the radiation properties of extragalactic jets

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Abstract. The origin of the synchrotron radiation from extragalactic jets is shown to be the interaction between the jet and the interstellar medium. This result is derived from a synthesis of available observations which strongly indicates that the one-sidedness is an intrinsic asymmetry. A plausible theoretical scheme is established and leads to the conclusion that the visible jet is interacting *less* with the interstellar medium than the invisible one (counterjet), contrary to a first intuition. The density asymmetry of the interstellar medium required by the theory is in agreement with the observations. This model does not only account for one-sidedness of extragalactic radiosources but more broadly for double sources with no or two visible jets, for the small number of optical jets, and for some other properties of radiosources.

Key words: Acceleration mechanisms – Galaxies: jets of – Interstellar medium: general – Quasars: jets of – Radio sources: general – Turbulence

1. Introduction

The gigantic and powerful radiosources seem to resist our investigations in spite of the huge efforts of both observers and theorists. The reason is that we do not have access to the dynamical component of the jet (often called the thermal or classical plasma). The radiation from which we get all the information is synchrotron radiation from relativistic electrons imbedded in a magnetic field the structure of which is still mysterious. The observation of the few optical jets has provided strong constraints on the physics of the jet because the particles responsible for this emission have a short lifetime so that they have to be accelerated in situ. And this optical emission is indeed the continuation of the radio synchrotron spectrum (Heavens & Meisenheimer 1987; Fraix-Burnet & Nieto 1988; Keel 1988; Biretta et al. 1991; Fraix-Burnet et al. 1991). Numerical simulations (Norman & Hardee 1988; Soker et al. 1988; Wilson 1987; Norman et al. 1982, 1984; Kössl et al. 1990a, 1990b, 1990c; Clarke & Burns 1991) have helped in understanding the propagation and stability of jets but they do not yet provide the detailed behaviour of the magnetic field and the synchrotron radiation. At the end, we do not know why there are different kinds of radiosources.

Three main classes of radiosources can be distinguished from the number of visible jets: 0, 1 or 2. According to Bridle & Perley (1984) radiosources are roughly equally distributed among these three classes. In 3C120, a convincing signature of the interaction between the counterjet (invisible) and the ISM has been found (Axon et al. 1989) confirming the idea that the ejections are intrinsically two-sided and that the jets can be invisible (see also Stiavelli et al. 1992; Sparks et al. 1992). If nearly all the radiosources have two lobes, indicating that there is a continuous supply of energy from the core to the lobes via visible or invisible jets, only five of them show an optical jet (M87, 3C66B, 3C273, PKS0521-36, and very probably 3C277.1 or Coma A). These optical jets are always one-sided but 3C66B has two visible radio jets. In all cases, the one-sided VLBI pc-scale jet (Pearson 1990) points toward the one-sided kpc-scale jet, except at least in 3C138 (Fanti et al. 1989). But some pc-scale jets are found in two-sided jet sources (e.g. NGC315, Venturi et al. 1990). Both apparent sub- and superluminal motions are observed. Relativistic beaming is often invoked to explain why only one jet is seen, but this does not explain why some radiosources have no or two visible jets and why only a few radio jets have optical emission.

To understand these different properties of radiosources, it is thus important to first understand the physical origin of the synchrotron radiation. The two most plausible mechanisms to accelerate particles in extragalactic jets (stochastic and diffusive shock accelerations) strongly rely on the properties of the magnetic turbulence, mainly Alfvén waves (Achterberg 1979; Ferrari et al. 1979; Eilek 1979; Drury 1983; Blandford & Eichler 1987; Fritz 1989; Fraix-Burnet & Pelletier 1991). The synchrotron properties of a jet thus depend on the properties of the turbulences.

In this paper I show both observational and theoretical evidences that the turbulences are generated by the interaction between the jet and the interstellar medium (ISM). This constitutes the basis of the model presented here by which the synchrotron radiation properties of a jet depend directly on the properties of the ISM which can be asymmetric. In Sect. 2, observational evidences for intrinsic asymmetries in radiosources are presented. Because of the lack a quantified theory of turbulences, only a theoretical outline of the model is given in Sect. 3. The consistency with the observations is made as quantitative as possible in Sect. 4. The conclusion is in Sect. 5.

2. Observational evidences for intrinsic asymmetry

2.1. The lobe properties/jet visibility correlation

Laing (1988) and Garrington et al. (1988) found a correlation between the jet side and the lobe depolarization. Two interpretations are possible: either the jets and the lobe depolarization are intrinsically asymmetric, or they are symmetric and relativistic beaming explains the correlation provided the depolarization is due to a galactic halo. Note however that there are exceptions in the correlation which are not easily understood in the frame of the second interpretation. Garrington et al. (1991) extended the study to a larger sample of one-sided sources. They confirm the previous result but also find a correlation between the jet side and the spectral index in the lobe. Liu & Pooley (1991a) in a sample of radiosources with no obvious jet also find a correlation between the spectral index and the depolarization.

In Fig. 1 (see also Fraix-Burnet 1992), the spectral index is plotted versus the depolarization parameter as defined by Liu & Pooley (with $DPM = (1 - DP) / (1 + DP)$ where DP is the ratio of the polarizations at 20 and 6 cm), using the data of Liu & Pooley (1991a), and those of Garrington et al. (1991) for which different symbols for jet- and counterjet-side lobes are used. There is a significant correlation between the two parameters (best linear fit: $\alpha = 0.82 + 0.36 DPM$, correlation coefficient = 0.53), confirming with a different presentation the result of Liu & Pooley: the less depolarized lobe has the flatter spectrum (see also Garrington & Conway 1991).

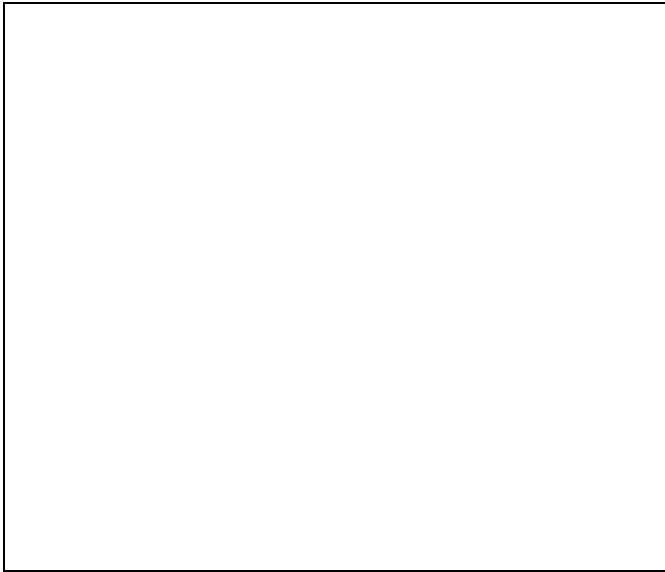


Fig. 1. Lobe spectral index (α) vs lobe depolarization (DPM, see text for definition). The data are from: \bullet : Garrington et al. (1991), jet-side; \circ : Garrington et al. (1991), counterjet-side; \times : Liu & Pooley (1991a). The solid line is the linear best fit, and the dashed lines delimitate the concentration of jet-side values.

More remarkably apparent on Fig. 1 is that the $\alpha(DPM)$ relation is true for jet-side as well as for counterjet-side. But the concentration of jet-side values indicates a correlation between jet visibility and lobe spectral index on one hand, and jet visibility and lobe depolarization on the other hand. Note that the relation also holds for data of Liu & Pooley taken apart.

This is important for two reasons. First, in their study, α is not only the spectral index of the hotspot but also the spectral index of the extended structure of the lobe so that it cannot be affected by relativistic aberration. Second the sources of their sample have no obvious jet.

There is a relatively large scatter in Fig. 1. This is not a surprise since no simple physical law can a priori relate α and DPM. Such a law will be investigated in Sect. 4.

The conclusion is that the *three* observables (visibility of a jet, depolarization and spectral index of a lobe) are correlated. Since, as pointed out by Garrington et al. (1991) and especially by Liu & Pooley (1991a), the spectral index asymmetry is certainly intrinsic (i.e. not due to any aberration), I conclude that *the asymmetries of the three observables are intrinsic* (Fraix-Burnet 1992).

2.2. The ISM asymmetry

Recently McCarthy et al. (1991) found that in powerful sources the emission line structures are nearly always brighter on the side of the lobe closer to the nucleus. They conclude that ‘this is a clear evidence of an intrinsically asymmetric property of powerful radiosources and provides the first direct evidence that environmental effects are responsible for the structural asymmetries’ in these sources. Already in 1984, Bridle noted from the same arguments that in some sources ‘the radio asymmetry is not due primarily to Doppler favoritism’.

Pedelty et al. (1989) show that, in sources without jet, there is a correlation between the distance of the lobe from the core and the depolarization. Interestingly, this correlation is also present in Fig. 6 of Garrington et al. (1991) for the counterjet side but is at most weak for the jet side. This is a strong indication that the invisibility of a jet has a common cause in all sources and thus cannot be due to Doppler dimming. Since the closer lobe is the more depolarized, the most probable origin for the correlation is the ISM. The question remains as to why the correlation is much weaker on the visible jet side? Since this lobe is less depolarized, it would be expected that it is systematically farther away. This does not seem to be true in general (Saikia 1984) and this is the case for only about 57% of the sources in the sample of Garrington et al. (1991). The interpretation of Garrington & Conway (1991), that the jet-side lobe is outside the depolarizing medium because it is closer to us (pointing toward us), is certainly not satisfactory since this does not explain the presence of this correlation in sources without jet and why the lobe-to-core distance is asymmetric in some of these sources. This is indeed an evidence of intrinsic asymmetry (Pedelty et al. 1989; Liu & Pooley 1991b). We will discuss the absence of correlation on the jet side in Sect. 4.

2.3. The case of M87

It is rather fortunate that the closest of the extragalactic jets (M87) is one-sided and has optical synchrotron emission. A detailed study of this object should tell us something about asymmetry. Owen et al. (1990) have undertaken a very detailed observation of the polarization of the whole radiosource. They find that the jet-side lobe is less depolarized in agreement with the general trend (Sect. 2.1), but they also find that the depolarization is much less in the jet than in the lobe. This is in complete contradiction with the interpretation of relativistic

beaming which would have expected a gradient of the depolarization along the jet in the sense of a decrease toward the lobe. Other counterexamples of this kind are pointed out by Pedelty et al. (1989). A more natural explanation is that the Faraday medium is around the lobe (Owen et al. 1990), i.e. rather local, so that any asymmetry in the depolarization is intrinsic.

Independently, high-dynamic range radio observations of this jet has ruled out relativistic beaming as the cause of the one-sidedness (Reid et al. 1989). Different arguments (Owen et al. 1989; Biretta et al. 1990) confirm that probably the jet has a velocity $< 0.5 c$ and lies within about 45° from the plane of the sky, so that it is certainly intrinsically one-sided.

Note that two other one-sided jets (NGC 6251 and Cygnus A) have been shown to lie near the plane of the sky (Jones 1987; Carilli et al. 1991), suggesting also an intrinsic origin for one-sidedness.

2.4. The detailed structure of the jets

The three-dimensional structure of the jet can be important in understanding the way it propagates and in finding where the relativistic particles are accelerated. At very high resolution (resolving details at least 10 times smaller than the jet width) it appears that jets present a hollow cylinder structure, the synchrotron emission being on the edges (Reid et al. 1989; Owen et al. 1989; Fraix-Burnet et al. 1989; Leahy & Perley 1991; Macchetto et al. 1991; Macchetto, 1992). The jets are also quite filamentary with no evidence for strong shock waves.

This is a strong indication that the synchrotron emission occurs on the edges of the jet at the interface between the jet and the ISM. It would leave the possibility that relativistic electrons propagate inside the jet where there is no magnetic field. They would thus need no reacceleration but they would have to diffuse in the boundary layer where the magnetic field is probably amplified by the turbulences (see Sect. 3.2.3). However a slight decrease of the spectral index and a more significant decrease of the synchrotron emissivity outward along the jet would be expected, but this is not observed in general. The particles are thus certainly reaccelerated inside the boundary layer.

2.5. Parsec-scale jets

Rapid variability in galactic nuclei and superluminal motions in VLBI pc-scale jets are the strongest indications of relativistic motions in the nuclei. Since all the observed motions are outward, relativistic beaming seems adequate to explain the one-sidedness of these pc-scale jets. However, thanks to higher quality data and a longer time span, it appears that the velocities we observe are phase velocities, not bulk velocities (Pearson 1990). In addition, it seems impossible to extract a relativistic jets because of the excessive Compton drag close to the central massive object (Henri & Pelletier 1991). The superluminal motions could then be explained by bursts of electron-positron pairs propagating inside the non-relativistic (or mildly relativistic) jet. This makes the extraction of a kpc-scale jet much easier energetically but puts into serious troubles the relativistic beaming interpretation of kpc-scale one-sidedness.

It is also often argued that since the pc-scale jet points always in the same direction as the one-sided kpc-scale jet, then relativistic aberration can explain one-sidedness at both scales. However this is not true at least in M87 (see Sect. 2.3)

and there is one counterexample (3C138, Fanti et al. 1989) where the pc-scale jet points on the other side than the kpc-scale one. There are also more and more constraints on 3C273 thanks to very high dynamic range observations (Davis et al. 1991). So the assumption of apparent asymmetry is not entirely satisfactory even at the parsec scale.

2.6. Conclusion

These observations strongly indicate that radiosources have intrinsically asymmetric properties which seem to be correlated with the asymmetry of the ISM. The interaction between the jet and the ISM is thus not only important for the heating of the ISM and for the propagation and stability of the jet, but also plays a role in the synchrotron radiation properties of the jet.

3. The physical origin of the synchrotron radiation

Since the different possible mechanisms invoqued to accelerate the particles responsible for the synchrotron radiation rely strongly on the magnetic turbulences (Achterberg 1979; Ferrari et al. 1979; Eilek 1979; Drury 1983; Blandford & Eichler 1987; Fritz 1989; Fraix-Burnet & Pelletier 1991), it is natural to search for the origin of these turbulences. The most intuitive origin is the interaction between the jet and the ISM and the previous section has shown that this is also strongly suggested by the observations. Indeed several studies (Eilek 1979; Ferrari et al. 1979; Bicknell & Melrose 1982; Eilek 1982; Eilek & Henriksen 1984) have dealt with this problem and in this section I briefly review the different steps leading from the jet/ISM interaction to the synchrotron radiation. The important parameters are emphasized in order to compare with the observations in a roughly quantitative way (Sect. 4).

3.1. Structure of the boundary layer

Numerical simulations have shown how much the structure of the boundary layer depends on the respective parameters of the jet and the surrounding medium. The two important parameters are: $\eta = \rho_j / \rho_{ISM}$ the ratio of internal to external densities, and $M = v_j / c_j$ the jet Mach number. Two extreme cases can be distinguished (Norman et al. 1984): a naked jet for a slow (low M) and heavy (high η) flow and a jet with a cocoon for a fast (high M) and light (low η) flow. The boundary between the two cases might not be sharp, but for a given M ($\gtrsim 5$), a factor of a few to 10 in η is certainly sufficient to modify quite dramatically the structure of the boundary layer between the jet and the ISM (see Fig. 1 and Plate 1 of Norman et al. 1984).

The efficiency of entrainment depends on the development of turbulences in the boundary layer: it is higher in a low- η and low- M ($\simeq 2 - 5$) jet, but the total amount of entrained matter is more important when $M \simeq 5 - 10$ (de Young 1986). In an inhomogeneous ISM, the behavior of the jet boundary may vary greatly along the jet and the entrained matter influences the boundary layer further away so that a large boundary layer can be maintained over a large distance.

3.2. Characteristics of the turbulences

3.2.1. Kelvin-Helmoltz turbulences

Kelvin-Helmoltz instabilities are essentially confined to the boundary layer. The scalelength of the turbulence of maximum growth rate is of the order of the jet radius and it slightly increases with the boundary layer width h . The small scalelength cut-off (i.e. the smallest unstable eddy) is of the order of h (Ferrari et al. 1982; Ray & Ershkovich 1983; Birkinshaw 1991). Whereas the density contrast η has a significant influence on scalelengths via h , it has little influence on growth rates (even though the instability is milder when $\eta \neq 1$).

In other words, when h increases, the energy provided to the turbulences increases because the scalelengths are larger but only slightly because the growth rates and the range of energy injection are smaller.

3.2.2. MHD turbulences

We know that the spectrum of magnetohydrodynamics (MHD) turbulences (generated by the Kelvin-Helmoltz instability; Eilek 1979; Ferrari et al. 1979; Bicknell & Melrose 1982; Eilek & Henriksen 1984) depends very much on the rate of energy injection from Kelvin-Helmoltz turbulences which is unknown and on the small scalelength cut-off which can be assumed to be of the order of the boundary layer width h (Sect. 3.2.1). A consequence of this process is that the turbulences are concentrated in the boundary layer.

In summary, MHD turbulences depend very much on h which is tightly linked to the characteristics of the Kelvin-Helmoltz turbulences and determines their smallest scalelength.

3.2.3. Magnetic field

The origin of the magnetic field in jet is still unknown but de Young (1980) has shown numerically that generation of magnetic field by turbulent dynamo is plausible. He found amplification factors of up to 10^4 - 10^5 with a degree of turbulence ($\langle (\delta B)^2 \rangle / \langle B^2 \rangle$) < 0.35 .

Since the MHD turbulences are essentially confined to the boundary layer (Sect. 3.2.2), the magnetic field will also be there. If the interstellar magnetic field is compressed around the jet, it will be also wrapped around the jet. This emphasizes the role of the boundary layer in the physics of the jet and points toward a hollow cylinder structure of the jet.

3.3. Particle acceleration

The most efficient mechanism to accelerate the electrons responsible for the synchrotron radiation in extragalactic jets is the diffusion of the electrons on magnetic turbulences around a shock wave (Drury 1983; Blandford & Eichler 1987). Recent calculations (Biermann & Strittmatter 1987; Heavens & Meisenheimer 1987; Fritz 1989; Fraix-Burnet & Pelletier 1991) have shown the high efficiency of this process to produce optical synchrotron emission. Fritz (1989) and Fraix-Burnet & Pelletier (1991) have found that the most important parameter is the degree of magnetic turbulences which must be very low especially in radio jets with no optical counterpart (Fraix-Burnet & Pelletier 1991). The diffusive shock acceleration mechanism might thus be *too* efficient (see also Fraix-Burnet 1992).

The stochastic mechanism is less efficient because there is no shock front but it is able to produce optical-radiating electrons with a degree of turbulence of the order unity (Eilek 1979, 1982; Bicknell & Melrose 1982). This is consistent with the result of de Young (1980; Sect. 3.2.3) and optical emission is expected to be much rarer than radio emission in agreement with the observations. This process has a relatively low efficiency, leading mainly to the heating of the thermal plasma of the jet (Achterberg 1979; Ferrari et al. 1979; Eilek 1979, 1982).

The particle acceleration is thus strongly correlated with the presence of MHD turbulences and occurs in the boundary layer. The efficiency of the acceleration mechanism depends essentially on the small scalelengths of the turbulences (Eilek 1979; Ferrari et al. 1982), hence on the boundary layer width h (Sect. 3.2.2).

3.4. Synchrotron radiation

It appears clearly now that the synchrotron spectrum must depend on the characteristics of the turbulences: these turbulences can both accelerate particles and generate magnetic field. The synchrotron radiation underlines the presence of all these processes and is thus expected to occur in the boundary layer. Since the synchrotron spectrum is determined by the efficiency of particle acceleration, the width h of the boundary layer plays a crucial role in the jet visibility. This parameter is determined by the density ratio η : when $\eta \simeq 1$, turbulences are important but h is very low and a lot of energy can go into the small scalelengths; when $\eta < 1$, the interaction of the jet with the ISM is stronger in the sense that h is higher, the entrained mass is more important and the turbulences are of larger scalelengths.

In simpler words, synchrotron radiation is expected to occur when h is low, that is when the jet does not interact too much with the ISM.

4. Discussion

The theoretical scheme presented in the previous section is currently the most logical complete explanation for the true origin of synchrotron emission in extragalactic jets. It is entirely physically plausible even though detailed calculations of the non-linear processes have not yet been performed. More importantly it provides a global understanding of the observations and especially those listed in Sect. 2. In this section I wish to detail a reinterpretation of some observations using this point of view.

4.1. Jet visibility

The synchrotron radiation is present for certain conditions of interaction between the jet and the ISM and this occurs mainly for heavy jets ($\eta \gtrsim 0.5$). So that invisible jets are light jets which interact strongly with the ISM. The implications on the ISM will be discussed in Sect. 4.3. Assuming there is a jet (visible or invisible) each time there is a visible lobe we find that there is roughly the same number of visible and invisible jets among radiosources (see Sect. 1). This is an indication that on average η is close to a limit we can put grossly around 0.5. Only about 2% of radio jets have optical emission at some level, but this is not surprising because of the fine tune-up of jet and

ISM parameters necessary to obtain optical synchrotron emission if, as probable, particles are accelerated by a stochastic mechanism (Sect. 3.3).

Synchrotron emission is also expected to give a hollow cylinder structure to the jets as observed in a growing number of cases (Sect. 2.6). It is worth noting that gaps in the inner part of jets can be explained in the same way since the jet is probably underdense close to the nucleus. It is also easy to understand why jets do not switch off after a certain distance from the core (since η increases outward), and why the invisible jets never switch on (because the entrained mass may maintain a low η).

4.2. The triple correlation: visibility/depolarization/spectral index

The triple correlation of Sect. 2.1 is naturally explained by the model presented here: the ISM on the invisible jet side should be denser and this is indeed indicated by the higher depolarization (since it is local, see Sect. 2). Note that the depolarization medium around the lobe can sometimes be different from the medium through which the jet propagates. We thus expect this correlation between lobe depolarization and jet visibility to suffer some exceptions like those present in Fig. 1. However the correlation indicates a certain level of homogeneity of the ISM.

Since the visible or invisible jets have different processes to loose energy, the injected energies into the corresponding lobes are expected to be different. The total energy of a jet is given by:

$$E_k = E_{\text{syn}} + E_B + E_{\text{heat}} + E_{\text{inj}}, \quad (1)$$

that is: jet kinetic energy = radiated energy + generated magnetic field energy + plasma and ISM heating energy + energy injected into the lobe.

The radiated energy can be estimated using a power law ($\nu^{-\alpha}$) with a typical spectral index $\alpha = 0.5$, a cut-off frequency at 10^{12} Hz and a typical spectral power density at 1.5 GHz of 10^{25} WHz^{-1} (Bridle & Perley 1984). One obtains:

$$\frac{E_k}{E_{\text{syn}}} \simeq 10^4 \dot{m} \left(\frac{v_j}{c} \right)^2 \simeq 10^2 \quad (2),$$

with plausible typical values for the mass flux in the jet $\dot{m} \simeq 1 \text{ M}_{\odot} \text{yr}^{-1}$ and for the jet velocity $v_j \simeq 0.1c$. This is only an indicative value since there are a lot of unknowns in this estimation and conditions may vary significantly from one source to the other, but we can reasonably assume in the following that the energy loss in synchrotron radiation is essentially negligible in a jet.

The turbulent generation of magnetic field is quite efficient since it does not require a lot of energy input. De Young (1980) estimates that it takes less than 10% of the energy injected into the turbulences which is a fraction of the jet kinetic energy. So the energy lost in the generation of the magnetic field can be assumed to be negligible.

It is difficult to estimate precisely the amount of jet kinetic energy that goes into heating the thermal plasma of the jet and the ISM. But following Eilek (1982) and Bicknell & Melrose (1982), most of the energy injected in the turbulences

is used to heat the thermal plasma in the stochastic acceleration process so that little is left to the particles themselves. This is in agreement with our estimation above that leads to a very low fraction of the jet kinetic energy into the synchrotron radiation.

In conclusion E_{heat} generally is the main energy sink for a jet and depends on the interaction between the jet and the ISM (it increases with h , see Sect. 3.2.1). Consequently, the energy E_{inj} available at the end of the jet and injected into the lobe depends significantly on this interaction so that the invisible jet is expected to provide less energy to the lobe. This is revealed by the steeper spectrum (higher spectral index) and more broadly by the correlation between DPM and α (Fig. 1) which is also true on the visible jet side.

With this plausible physical link between α and DPM, one can try to transform Fig. 1 into a more physical plot. To test the model proposed here, it is legitimate to calculate the total synchrotron emission from the lobe versus some function of DPM that can be related to the properties of the ISM. This function will be given by the depolarization due to a foreground screen (Garrington & Conway 1991):

$$(1+z)^2 \sqrt{-\ln(DP)} = \frac{\rho_{\text{ISM}} B L}{22}. \quad (3)$$

where B and L are respectively the magnetic field and the dimension along the line-of-sight of the ISM causing the depolarization. The correlation (Fig. 2) between α and the quantity given in Eq. 3 is significantly better than between α and DP (Fig. 1). The correlation coefficient of the linear regression is nearly the same as in Fig. 1, i.e. 0.51 (but there are less points since lobes with $DP > 1$ or $DPM < 0$ have been omitted), but if we remove the four points to the right (corresponding all to invisible jet side and to sources with $z > 2$), the coefficient becomes 0.64. This rather tight correlation confirms the hypothesis made in this paper that the physical properties of the lobe (which depend on the energy injected by the jet) depend on the properties of the ISM around the lobe (which are certainly representative of conditions around the jet). The dispersion in Fig. 2, and especially the four right points, is probably explained by the two variables B and L which are not directly related to α .

To definitively test the model presented in this paper, it would be preferable to find a better estimation of the energy injected (E_{inj}) into the lobe than the spectral index. The total synchrotron emission ($E_{\text{syn,lobe}}$) from the lobe is only an underestimate of E_{inj} , but this is the most directly observable parameter that can be used to evaluate the energy inside the lobe. Indeed the ratio $E_{\text{syn,lobe}}/E_{\text{inj}}$ is probably small in general and may vary greatly from one lobe to the other. The synchrotron emission energy per unit of time $\dot{E}_{\text{syn,lobe}}$ can be estimated as:

$$\dot{E}_{\text{syn,lobe}} = 1.1 \cdot 10^{20} D_{\text{Mpc}}^2 S_{Jy} \frac{\nu_0^{1-\alpha}}{1-\alpha} [\nu_2^{1-\alpha} - \nu_1^{1-\alpha}] \text{ W}, \quad (4)$$

where D_{Mpc} is calculated using $H = 75 \text{ kms}^{-1} \text{Mpc}^{-1}$ and $q = 0.5$, S_{Jy} at frequency ν_0 and α are given by Garrington et al. (1991) and Liu & Pooley (1991a). Since ν_1 and ν_2 are unknown, I choose $\nu_1 = 10^8$ Hz and $\nu_2 = 10^{11}$ Hz even though these values should be different for each lobe. This rigid choice necessarily results in an artificial scatter in the plot (Fig. 3). In the frame of the model of this paper, a bias is also expected

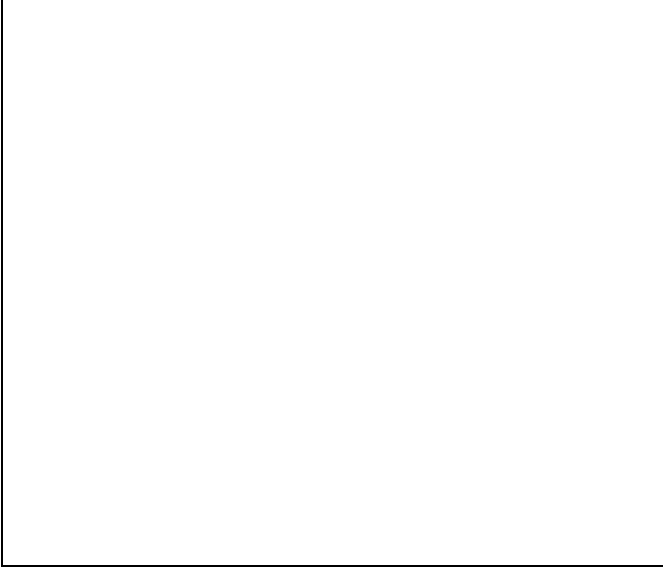


Fig. 2. Spectral index of the lobe vs $(1+z)^2 \sqrt{-\ln(\text{DP})}$ with the same symbols as in Fig. 1.



Fig. 3. Synchrotron lobe power vs $(1+z)^2 \sqrt{-\ln(\text{DP})}$ with the same symbols as in Fig. 1.

since ν_2 (and to a lesser degree ν_1) depends on the injected energy and is thus underestimated for low ρ_{ISM} . Consequently, $\dot{E}_{\text{syn,lobe}}$ is also underestimated while it can be shown that it is probably slightly overestimated for high ρ_{ISM} .

No obvious trend is seen in Fig. 3 but if the expected bias is taken into account, there is a consistency with the prediction of the model that $\dot{E}_{\text{syn,lobe}}$ should slightly decrease when ρ_{ISM} increases. Note also that only 23% of the sources (of the Garrington et al. sample) have a higher $\dot{E}_{\text{syn,lobe}}$ on the invisible jet side (see also Christiansen 1984). All this tends to confirm the fact that more energy is injected into the lobe when the ISM density is lower, in particular when the jet is visible. At this level, a detailed understanding of the physics of the lobe

is required, but this is not available and beyond the scope of this paper.

4.3. The ISM asymmetry

In this paper, one-sidedness is simply explained by an asymmetry of the ISM density. While the observations show convincing evidences for asymmetric ISM, it is necessary to quantify the level of density asymmetry required to explain one-sidedness. It will be assumed that the two opposite jets have similar properties, i.e. density and velocity. This is consistent with the most accepted formation process of jets from accretions disks.

In Sect. 3.1, we have seen that a ratio of 2 to 10 in ISM density is sufficient to distinguish between the two regimes with and without a cocoon. From theoretical considerations it is thus possible to say that on the invisible jet side, the ISM should be denser by a factor $\simeq 2 - 10$.

On the observational side, there are at least two ways of deriving an order of magnitude of the density asymmetry. The first one uses the depolarization itself. Using Eq. 2, an histogram of the ratio of $\rho_{\text{ISM}} BL$ on the two sides is plotted in Fig. 4. Since we want an estimation of the ISM density asymmetry and since the depolarization is sometimes higher on the jet side, the ratio has been made larger than 1 so that it does not correspond to visible jet side vs invisible jet side. The predominant values are between 1 and 4 and very few are above. Note that the sources of Liu & Pooley (1991a), which have no obvious jet, have a more symmetric ISM.

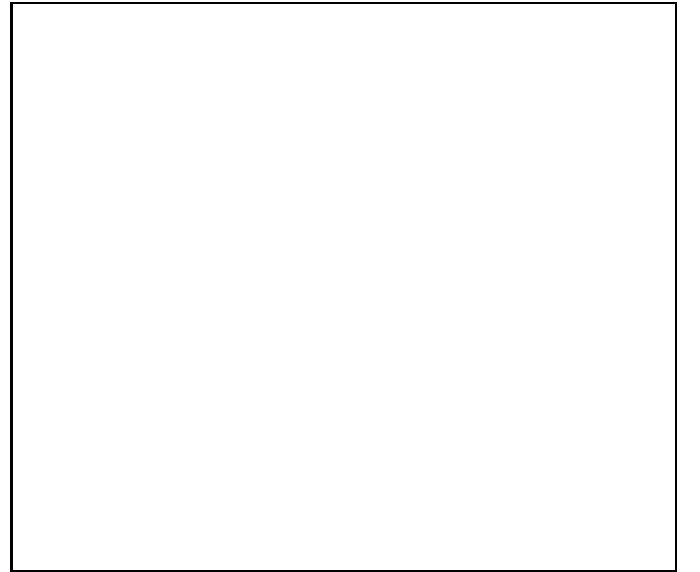


Fig. 4. Histogram of the ratio (> 1) of $\rho_{\text{ISM}} BL$ on the two sides of the radiosources. The solid line includes only the data of Garrington et al. (1991) whereas the dashed line includes also the data of Liu & Pooley (1991a).

The X-ray observations provide a second estimate of the density asymmetry. Even if the level of precision of the observations is barely sufficient for this purpose, it is possible to derive that density ratios up to 10 are quite consistent with the data (Trinchieri et al. 1986).

From a statistical comparison of lobe synchrotron emission and distance from the core, Swarup & Banhatti (1981) infer

ISM density variations of a factor of 2 over scales of several tens of kpc (smaller than radio source sizes).

It appears that the density asymmetry derived from the observations is less than about 10 and more probably of the order of 2 to 4. This is consistent with what is required from the theory.

An interesting point is that if radio activity is brought through the ISM falling onto the nucleus, then powerful radio sources might have quite an asymmetric ISM. This could explain why powerful radio sources tend to be one-sided.

Since the invisible jet side lobe is not systematically closer to the visible jet side lobe (Saikia 1984), the core-to-lobe distance must not depend very much on the energy of the jet. The lobe is then not the result of the energetic exhausting of the jet through the drag by the ISM, but rather corresponds to the disruption of the jet due to a growing instability or to the effect of the intergalactic medium. This is indeed the only way to understand the correlation between distance and depolarization (Sect. 2.2) which is nearly absent when the jet is visible: since the depolarization is weak on the jet side, the correlation will be consequently weak whereas on the invisible jet side the correlation reflects the distribution of ISM with distance from the core.

Why the radiative properties of a jet are maintained over large distances (up to a few Mpc for some jets in quasars)? In fact it seems that the most common situation is $\eta < 0.5 - 1$ which implies synchrotron visibility. As a consequence, an explanation must be found for invisibility over large distances. As already proposed (Sect. 4.1), the entrained mass might maintain η at a low value, or for an unknown reason it might maintain large scalelength turbulences.

4.4. What about the pc-scale asymmetry?

The main problem with this model is currently to understand why most pc-scale jets point toward the visible kpc-scale jet. Since it is impossible to extract a relativistic jet because of the Compton drag (Henri & Pelletier 1991), the synchrotron emission process that reveals relativistic motions at the pc-scale must be different from the emission process at the kpc-scale: electron-positron pairs at the pc-scale and accelerated relativistic electrons at the kpc-scale, both in a non relativistic jet. So that beaming at the large scale cannot be derived from relativistic motions at the small scale. But why these emission processes should be correlated most of the time? It will be necessary to work this out, but, since one-sidedness at the pc-scale is probably intrinsic at least in some cases (Sects. 2.3 and 2.5), this could be because there is also an asymmetry in the environment of the pc-scale jet (magnetic field, ISM) that is somehow linked to the kpc-scale ISM asymmetry.

5. Conclusion

A new point of view has been presented in this paper: contrary to a first intuition, the visible jet propagates more efficiently than the invisible jet. The main reason for this statement is that jet visibility is correlated with the spectral index of the corresponding lobe indicating that more energy is injected into the lobe when the jet is visible. But this is also supported by theoretical arguments showing that synchrotron emission should occur in the boundary layer of the jet and that this

boundary layer must not be too large for the particle acceleration to be efficient. And the structure of this boundary layer is determined by the interaction between the jet and the ISM, the layer being larger when the ISM is denser.

The principal consequence of the model is that one-sidedness is explained by an asymmetry of the ISM in agreement with a growing number of observational evidences for intrinsically asymmetric properties of radio sources and of ionized gas in radio sources. The level of density asymmetry required from theoretical arguments is shown to be quite consistent with observational estimations. The principal advantage of the present model is to provide a global physical understanding of large-scale radio sources and of the jet visibility in particular. Even though some relativistic beaming can occur sometimes, it never plays the principal role in large-scale radio sources because of inconsistencies with the ensemble of the observations.

The present model relies mainly on non-linear physics and more detailed theories would help to quantify the different energies involved. But hopefully this model will provide a frame in which theorists can work and that can be useful for numerical simulations. And the observers should be encouraged to have a closer look at the invisible side of radio sources.

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